Abstract

The structural design of a civil tiltrotor (CTR) wing box, made of graphite-epoxy material, for minimum weight is considered. The wing is designed to satisfy all static and dynamic constraints. The static constraints are determined based on the applied stresses and the strength allowables while the dynamic constraints are determined based on the magnitudes of the first natural frequencies in bending and torsion and their relative placement. With focus on the structural design, the wing's aerodynamic shape and the tip arrangement (i.e., rotor, engine, nacelle, etc) are held fixed. The initial design requirement on drag reduction set the airfoil maximum thickness-to-chord ratio to 18%. The airfoil section is the scaled down version of the 23%-thick airfoil used in V-22 wing.

The analysis and design studies are based on two different finite-element computer codes: (a) MSC/NASTRAN, and (b) the modified version of WIDOWAC. Several test cases have been studied for the comparison of the two finite element codes. Preliminary studies using simple wing models yielded good agreement between the MSC/NASTRAN and WIDOWAC analysis results for both isotropic and orthotropic materials. For geometrically complex models such as the CTR wing, the limitations in WIDOWAC make the comparison of the results with those of MSC/NASTRAN rather difficult.

To allow for the maximum tailoring of the structure and hence arriving at the minimum-weight design, variations in the number of stringers as well as their cross-sectional dimensions have been considered in the NASTRAN model. The trade-offs between the areas of the stringers and spar caps are evident in the results. Also the skin plies are oriented at angles which maximize the contribution of the skin to bending as well as torsional stiffness of the wing structure.

Background

Initial investigations led to the better understanding of the structural dynamic and aeroelastic characteristics of the tiltrotor configuration, and the identification of proper procedures to analyze and account for these characteristics in the wing design. This investigation resulted in a collection of numerous technical papers on the subject—some of which have been referenced here. The review of literature on the tiltrotor revealed the complexity of the system in terms of wing-rotor-pylon interactions.[1] The aeroelastic instability or whirl flutter stemming from wing-rotor-pylon interactions is found to be the most critical mode of instability demanding careful consideration in the preliminary wing design.[2-8] The placement of wing fundamental natural frequencies in bending and torsion relative to each other and relative to the rotor 1/rev frequencies is found to have a strong influence on the whirl flutter.[9] The frequency placement guide based on a Bell Helicopter Textron study[10] is used in the formulation of dynamic constraints. The preliminary findings are summarized in Ref. 11.

Wing Design Problem

The design problem is to find the optimum set of structural parameters that minimizes the cantilever wing structural weight while satisfying all static and dynamic constraints. The optimization problem is formulated as follows: Determine the optimum set of design variables to

Minimize $\quad W(X)$

Subject to $\quad g_s(X) \geq 0$

$\qquad\qquad g_d(X) \geq 0,$

where W denotes the wing structural weight. The quantities g_s and g_d represent the static and dynamic constraints, respectively. The vector of design variables is represented by X. The static constraints are formulated in terms of strength allowables while the dynamic constraints are formulated in terms of wing bending and torsion natural frequencies and the frequencies of the rotor system. The design variables include skin ply thicknesses and orientation angles (NASTRAN model only), the spar web and rib web thicknesses and spar-cap and stringer cross-sectional areas. These design variables will allow the tailoring of the composite wing structure to meet the design requirements most efficiently.

MSC/NASTRAN Model

MSC/PATRAN software package was used to create the finite-element model of the wing for MSC/NASTRAN analysis and design studies. The model is based on the 18% thick airfoil derived from the V22 wing. In MSC/NASTRAN the skin is modeled by CQUAD4 elements with membrane properties specified in the Pshell; the spar caps are modeled by ROD elements with the shear webs modeled by CQUAD4 elements.

Three different arrangements with varying degrees of complexity were used to model the wing-tip mounted rotor-nacelle system. In the last model that is considerably more accurate than the other two, the engine, transmission, nacelle, rotor, etc, are represented by a series of relatively rigid one-dimensional elements with the mass of each component lumped at an appropriate node. The information with regard to each individual component is obtained from Ref. 10.

The tip structure is then attached to the wing box at the spindle location. In the actual aircraft the entire nacelle-rotor system pivots about the spindle as the aircraft transforms back and forth between vertical and horizontal flight modes. The non-structural masses, associated with fuel, flight control system, etc. inside the wing, are lumped at the finite-element nodes in the vicinity of corresponding C.G. locations.

WIDOWAC Model

As part of the research task the WIDOWAC[11] wing structural analysis/design code was examined for possible use in the support of structural tailoring activities. After a series of program modifications and subsequent validation, the code was ready to use for the CTR wing analysis and design. Additional modifications were performed to include dynamic constraints in the design optimization routine of WIDOWAC. The latest modifications allow for the specification of limits on the first three natural frequencies of the wing structure. As the program is set up right now, the limits are imposed as an upper bound on the first natural frequency and lower bounds on the second and third. In WIDOWAC the skin is modeled by linear membrane elements, the spar caps are modeled by linear rod elements and the spar and rib webs are modeled by linear (symmetric) shear web elements.

With a desired WIDOWAC wing model and corresponding input file set up, an analysis run is performed to determine the vibration modes corresponding to the first vertical bending and first torsion. By identifying which two of the first three modes correspond to the first bending and torsion, in the subsequent design run the associated constraints can be turned on (i.e., set to TRUE) while the third one can be turned off (i.e., set to FALSE).

As far as the optimization capabilities are concerned, WIDOWAC searches for an improved design in the feasible design region using an interior penalty function method. This method requires the initial design to be feasible, hence in most instances it is necessary to first identify a feasible design which by itself can be a very time consuming task. The speed at which a converged solution can be obtained depends on the number of design variables selected and the value of the penalty multiplier started out with. A "wrong" choice

of penalty multiplier could send WIDOWAC into a wild goose chase with no means of automatic recovery. Getting the optimization to work is not a trivial task.

Summary of Results

To validate the analysis capabilities of WIDOWAC, four test cases were first examined with the results compared to those obtained from MSC/NASTRAN. These test cases are all based on a symmetric, straight and untapered wing model with five spars and eight ribs.

In the first and second test cases we examined the vibration characteristics of a straight isotropic wing and its static response to: (1) pure torsion, and (2) bending-torsion combination. The WIDOWAC- and MSC/NASTRAN-based modal analysis gave almost identical results for bending natural frequencies, but the first torsion natural frequency obtained from WIDOWAC was about 10% higher than that obtained from MSC/NASTRAN. This discrepancy is attributed to the subtle differences in the two-dimensional elements used in these codes to model the skin and shear webs, which provide the bulk of torsional stiffness. The WIDOWAC- and MSC/NASTRAN-based nodal displacements were in very good agreement for both static loading conditions. As far as the stress components are concerned, the agreement for the first loading condition was much better than the second. The only reasonable explanation is that there must be some differences in the way element strains are calculated from the nodal displacements in the postprocessing. While these differences did not matter in the pure torsion case they did affect the stress results in the combined bending-torsion problem.

In the third and fourth test cases we examined the vibration characteristics of a straight orthotropic (with a 0°/90° layered skin) wing and its static response to: (1) pure torsion, and (2) bending-torsion combination. The WIDOWAC- and MSC/NASTRAN-based results for modal and static analysis compared fairly well.

Examination of the CTR wing followed the conclusion of the symmetric wing case studies. Three different NASTRAN models of the CTR wing with variations in the tip structure were examined. The knowledge gained from the NASTRAN analysis runs helped with the modeling of the tip structure for WIDOWAC analysis and design studies.

A NASTRAN model was used for the design of the CTR wing based on three different initial designs in terms of skin plies orientation angles. The loading conditions were selected among those given in Ref. 10. Both static and modal analysis solutions were combined with an optimization solution in the MSC/NASTRAN bulk data deck. The design analysis was performed subject to static and dynamic constraints. The results of this study are discussed in Ref. 13.

With the WIDOWAC CTR wing model certain restrictions had to be imposed. Since WIDOWAC requires the wing model to be symmetric through the shear-web-element definition, it was necessary to model the tip structure symmetrically as well. With this restriction in mind, the tip structure was modeled as close to the actual structure as possible. A single loading condition was used for the analysis and optimization. The design variables in WIDOWAC are limited to the sizing variables and do not include the ply orientation angles. Ply orientations of ±45° and ±45°/0°/90° have been used for the skin elements in two different analysis and design studies of the WIDOWAC CTR wing model. While the analysis runs have been completed, the design cases are still not completely finished.

With greater modeling flexibility in NASTRAN, we have considered expanding the tailoring possibility of the structure to include variation in the number of stringers that are used to support the upper and lower skin panels. In addition, instead of the two loading conditions used earlier, we have included four more that cover all three main flight modes (i.e., airplane, helicopter, and conversion). This addition requires changing the finite-element

model of the wing due to changes in the number of stringers as well as changing the tip structure to match the nacelle position in each flight mode.

The results of this latest study are hoped to be presented at the next AIAA SDM conference. The detailed discussion for all the cases examined are being compiled to be published in a NASA technical report.

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A preliminary study was conducted toward the optimum design of a composite wing-box structure for a civil tilt-rotor transport aircraft. This effort has been focused on two tasks: (1) to study the intricate dynamic and aeroelastic characteristics of the tilt-rotor configuration, and to identify the proper procedures to analyze these characteristics; and (2) to develop the structural modeling and analysis techniques necessary in the tilt-rotor wing design optimization. Following the completion of this task, and proper formulation of aeroelastic and structural constraints, the design optimization will proceed to develop a minimum-weight, tailored, lower-drag wing design. In the preliminary design of the wing-box structure, the design variables will include only structural parameters such as thicknesses and orientation angles of the upper and lower-skin plies, spar and rib cap areas and web thicknesses, and stringer areas. The wing-rotor-pylon aeroelastic and dynamic interactions will be limited in the preliminary wing design by holding the cruise speed, rotor-pylon system and wing geometric attributes fixed.

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In this study, the problem of optimizing a composite wing-box structure for a civil tilt-rotor aircraft is considered. The vibrational characteristics of the tilt-rotor system are examined, and the potential instabilities are avoided in the preliminary design by means of dynamic constraints. Two critical flight loading conditions are established. Based on three initial models, an optimization analysis is performed to minimize the structural weight of the wing-box by tailoring the thickness and orientation of each ply in the composite skin and varying the cross-sectional areas of the stringers and spar caps and the thickness of the spar webs. At the end, an optimum design is obtained that satisfied the dynamic and structural constraints at a minimum structural weight. The structural analysis and design in this study are conducted using MSC/NASTRAN finite-element code.